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PROPOSAL FOR QUENCH-TEST ON NB3SN SMALL COIL

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Abstract:

In the R&D effort towards a post-LHC hadron collider, Fermilab and LBNL are developing 10-15 T Nb_3Sn dipole magnets using several design approaches. These magnets use Nb3Sn superconductor technology. Nb3Sn is a brittle material and it is yet not well known how much it may be affected by thermo-mechanical stress/strain during a magnet quench inducing temperatures above 300 K at the hot spot. Rapid thermal expansion of conductor and large temperature gradients during a magnet quench can result in permanent critical current degradation and thus affect the performance of a magnet. Especially for the design of efficient quench protection systems, it is necessary to define the maximum temperatures that can be attained in the coils during a quench. Although critical current versus strain data are well known for Nb3Sn, little is known about how to apply these limitations to the case of a cable thermally expanding in a magnet during a quench. To measure the effect of the thermo-mechanical jolt exerted on the conductor during a quench the following experimental approach is proposed.

1.0 INTRODUCTION

During quenches in superconducting magnets, parts of the coils can reach very high temperatures if the proper protection measures are not taken. Nevertheless, even in the case of actively protected magnets, it has to be determined which level of temperatures and voltages can be sustained by the magnet parts. An upper temperature limit is given by the melting point of the soldering (~500 K), since the quench might start near the conductor joints. For impregnated coils, a second limit could be the glass transition point of the insulation, which occurs at about 400 K for epoxy resins. At that temperature, the epoxy becomes soft and, even if the transition is reversible, the changes in its electrical properties increase the probability of a short circuit. In the case of magnets using Nb_3Sn superconductor, an additional complexity is introduced via the brittleness of Nb_3Sn, which can be permanently degraded in its current carrying capability, under the effect of stress. Simulations of the quench process for Fermilab's Nb_3Sn magnets [1] have revealed the lack of data for the maximum acceptable temperature that strongly affect the size/cost of the active quench protection system.

There are various possible ways to estimate the effect of magnet quenching and the ensuing thermo-mechanical stress on the critical current of brittle Nb_3Sn conductor. One way is to use finite element model calculations of the stresses/strains induced in the conductor during a magnet quench (including a simulation of the magnet quench process itself) related to the well-known critical-current versus strain characteristics of Nb_3Sn strands. Efforts to obtain a result from calculations with this approach are underway at Fermilab and LBNL. A second way is to perform experiments that reproduce as realistically as possible the thermo-mechanical conditions in a cable during a magnet quench. A first experiment was performed on cables, within a collaboration FNAL-NHMFL. The experiment is briefly summarized in 3.0, and described in details in [2]. Here we present the plan for the continuation of the experimental program on small coils, within a collaboration FNAL-LBNL.

2.0 CONCEPT OF THE EXPERIMENT

The coils are instrumented with a spot heater each, and two voltage taps across the spot heater section. The magnet is trained until a quench plateau is reached.

At a current below the quench current, a quench is started with one spot heater. The quench is left propagating along the cable instead of switching off the current immediately, using a pre-defined delay. The current in the normal-conducting matrix allows a well-defined amount of heating of the cable. The normal conducting zone propagates in the coil, with a temperature profile that goes from the peak temperature of the starting point, to the bath temperature in other regions of the coils and in the supporting structure. The temperature gradients that are created in this fast process can induce the sought thermo-mechanical stress. Repeated measurements of the quench current of the coils, after each excursion to high temperatures, allow assessing the critical current degradation as a function of the peak temperature during a quench.

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[1] L. Imbasciati et al., "Quench Protection of High Field Nb_3Sn Magnets For VLHC", proceedings of PAC, June 2001;

[2] L. Imbasciati et al., "Quench-Tests On Nb3Sn Cables - Run 1", TD-note TD-01-075, November 2001;

3.0 FIRST RUN

The experiments performed at NHMFL utilized a setting similar to that of critical current measurements of cables.

- The samples tested in this series were wound from 41, 0.7 mm diameter, ITER-type Nb_3Sn/Cu strands with a Cu/non-Cu=1.4, without core. One set of samples was reacted straight, while another set was reacted on a spool and straightened after reaction during the sample-holder assembly, to measure the degradation of the critical current due to bending.
- The magnetic field and the current were set to 8 T / 8 kA, in order to operate near the critical surface of the samples.
- The results of this first experiment showed no critical current degradation after reaching peak temperatures up to 420 K. The temperature in the straight sample actually reached 490 K during the last quench test. After the quench test, during the critical current measurement, an early quench occurred at 8820 A. The data don't show a transition curve, it's not possible therefore to estimate the critical current value, and infer a sign of degradation of the conductor. There are clear signs instead, that the insulation was damaged.

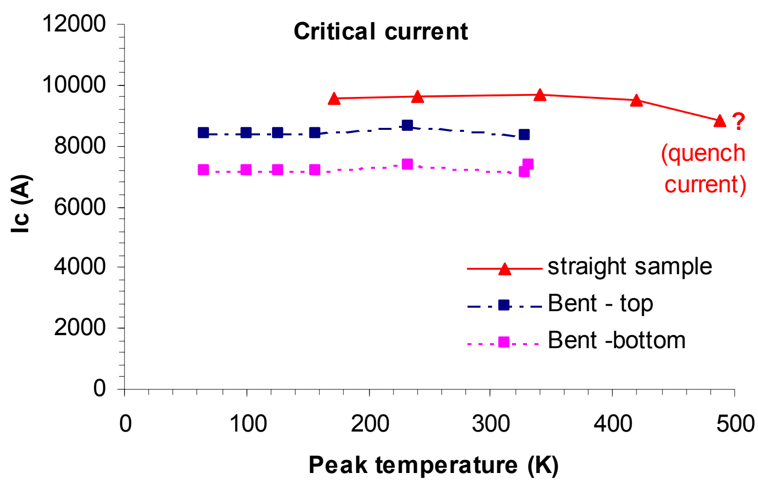

Figure 1: Results of the first run: critical current vs. peak temperature.

- Quenching of the background magnet interrupted the quench test series for both samples. One possible cause of the magnet quenches is believed to be heat exchange between magnet and cable sample holder. Signs of burnings appeared on the straight samples, but not on the bent one. Other possible causes of magnet quench are mechanical movement of the sample or an electrical failure.
- For the next test run, the use of sub-sized cables with state of the art conductor is proposed. To measure the critical current of this conductor, higher current in the samples and/or a higher magnetic field are necessary. This would require several modifications to the cable sample holder and to the test facility, but would not eliminate completely the risk of a quench of the magnet.

4.0 QUENCH TEST PROPOSAL

The use of LBL small coils allows a continuation and even an improvement of the quench tests program. In fact, the facility at LBL is designed to measure the critical current of sub-sized cables with state of the art conductor. In addition, the quenched cable will be set in a mechanical environment more similar to that of a magnet. The protection of the accelerator magnets is the ultimate goal, but it is more advantageous to perform the quench test on small coils. In order to clearly see a degradation of the critical current it is necessary to operate the magnet close to the short sample limit, or to reach a reproducible quench current (flat plateau). In additions, there are other motivations such as cost, helium consumption, and time required for construction.

4.1 Small Coils main features

These are the general features of the small coil magnets:

- Two-layer racetrack **coils**
  – 5 kg of conductor per coil
  – Field range: 8 - 12 tesla
  – I_{MAX} ~ 10 kA
  – L_{MAGNET}: 0.2 - 0.4 mH
  – I_{SS}: 8300 - 9600 A
  – $J_{non\text{-}Cu}$: 2200 - 2700 A/mm^2
  – J_{Cu}: 1800 – 2700 A/mm^2
  – E_{STORED} < 20 kJ

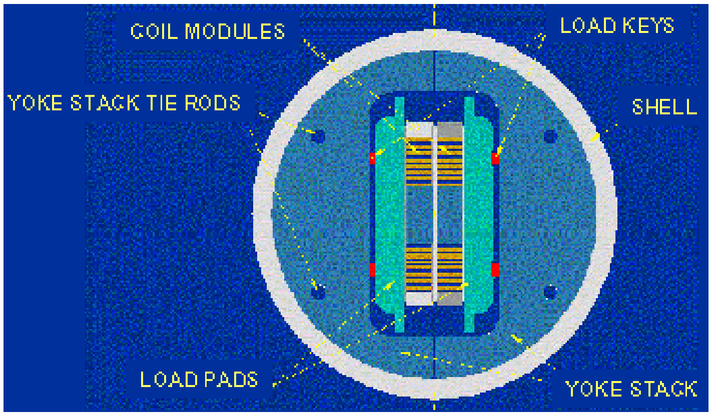

Figure 2: Small coil cross-section.

- **Test facility**
  – Small dewar (no refrigerator)
  – two different data loggers for data acquisition
  – Energy extraction trough external dump resistor (~ 50 mΩ)

- **Instrumentation**
  – a spot heater for each module in the end region
  – a couple of voltage taps across each splice
  – a temperature sensor for each module close to splices
  – resistive strain gauges (shell)
  – no quench protection heaters

- **New instrumentation for the quench test**
  - New spot heater design (see appendix).
  - Voltage taps across spot heater: each voltage tap should be about one pitch length (55 mm) apart from the spot heater.

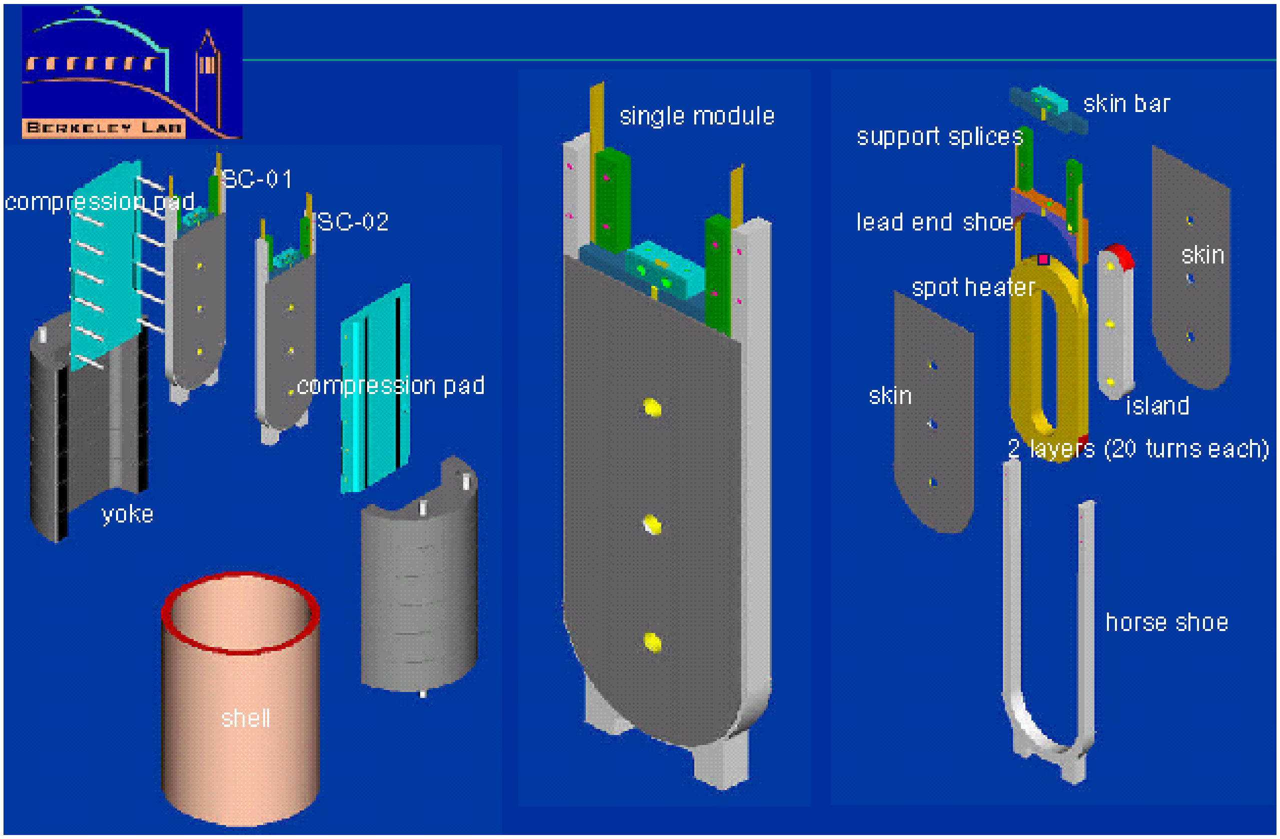

Figure 3: Magnet assembly.

- The baseline **conductor**, on which the following calculations are based, is Oxford MJR Nb_3Sn conductor, with the following specifications:

- N of strands	20
- Cu:SC	0.869
- Cable width (mm)	7.94
- Cable thickness (mm)	1.28
- Strand diameter (mm)	0.7103
- Pitch angle	15.9
- Packing factor	0.83
- J_C (A/mm^2) @12T/4.2K	2200
- I_{SS} (A)	9800
- B_{peak} (T) in the coil at Iss	11.8
- Cu RRR	40
- Insulation (mm)	0.15 = total turn-to-turn = 2 x (60 µm fiberglass + 13 µm Kapton).

- The **coil geometry** is shown in figure 4.

- The **field distribution** is shown in figure 5

- In figure 4 and 5 is also indicated the **spot heater position**. It is important to put the spot heater in a relatively high field region (inner layer), so that the effect of local degradation may result in a quench current reduction. For the same reason, it should be considered if it is possible to install the spot heater in straight section. From the mechanical point of view, previous experiences with HFDB magnets (racetrack magnets with react and wind technology) indicate that the spot heaters on the innermost turn are easier to install and to protect from damage during assembly.

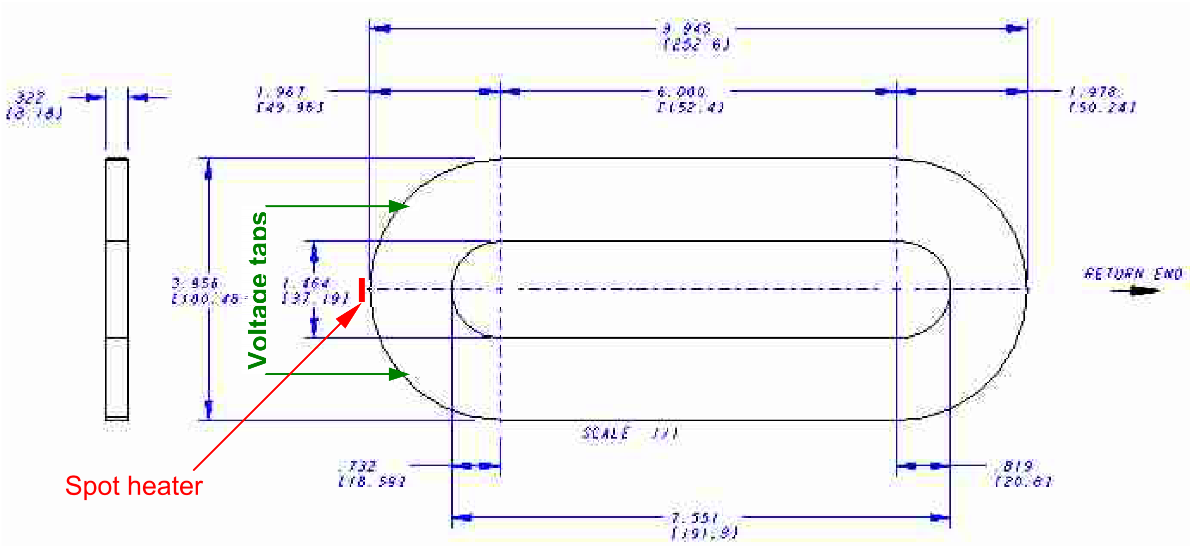

Figure 4: Coil geometry (all dimensions in inches [mm]).

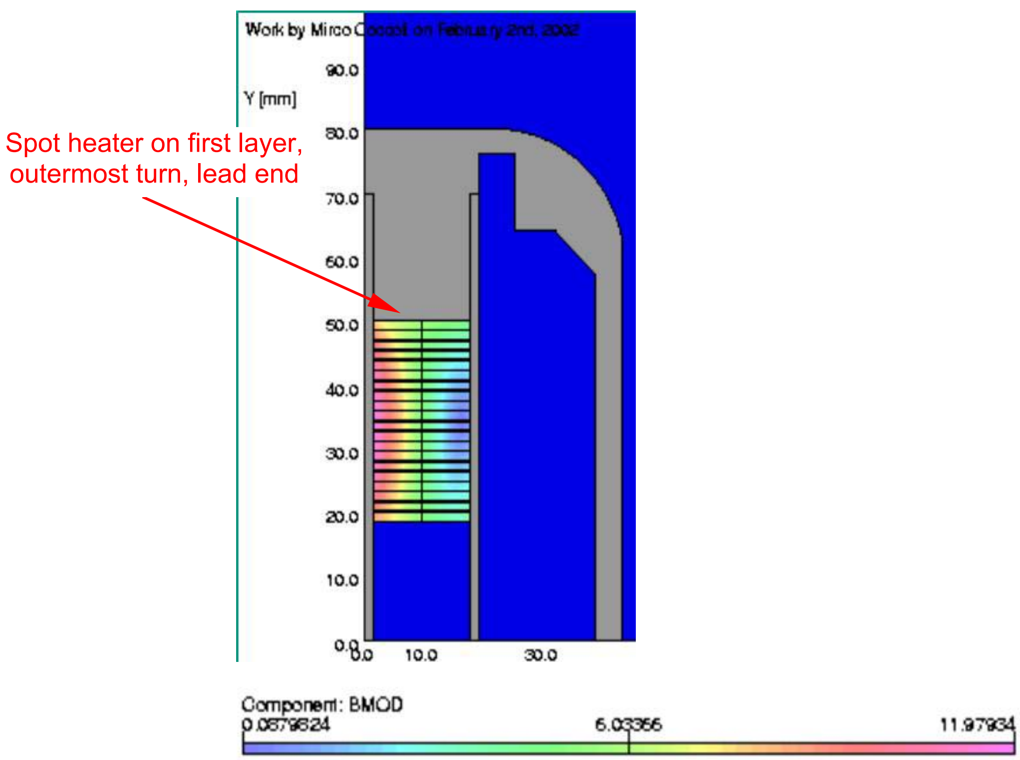

Figure 5: magnetic field intensity (tesla) in one quadrant of the small coil magnet.

5.0 SIMULATION OF THE EXPERIMENTS

A model, described in the following, has been used to calculate the voltages and temperatures occurring in the magnet during a quench with different dump delay times. The thermal model is adiabatic, relating the local cable temperature to the heat generated by the current in the normal-conducting matrix. As usual for the superconducting magnet protection, the temperature is calculated from the quench integral QI, that is defined via the current decay profile or material properties (specific heat c_p, resistivity ρ) (1). I is the current in the sample, A is the total cable cross-sectional surface, T(t) the temperature of the sample at time t, the subscript *comp* refers to the composite nature of the material (containing copper, Nb3Sn, bronze, epoxy and insulation), and thus denotes an average specific heat, calculated from the rule of mixture.

$$QI = 10^{-6}\int_0^t I^2(t')dt' = 10^{-6}A^2\int_{T_0}^{T(t)}\frac{c_{comp}(T')}{\rho(T')}dT' \quad MIIts \tag{1}$$

Figure 6 shows the temperature versus quench integral, calculated with (1) for the conductor described above. A quench integral of **5.5 MA^{2}s** corresponds to a temperature of **400 K**.

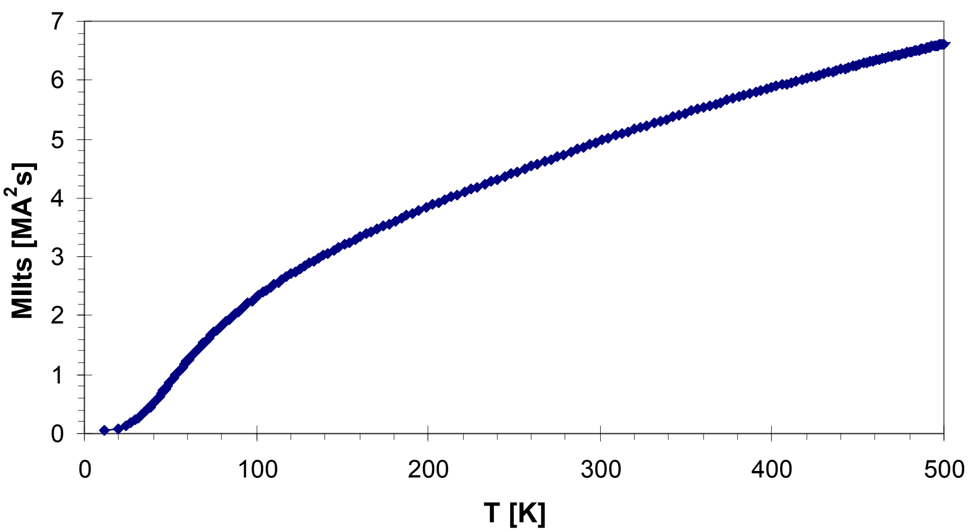

Figure 6: quench integral accumulated during the quench process as a function of peak temperature, in the quench simulations.

Figures 7-9 show temperature, current and voltage, as a function of time during a quench at 9500 A. The simulation of the quench assumes a quench starting at t=0 in the lead end region of the inner layer of one module. The magnetic field at the starting point is ~9 T. The quench then spreads through the inner layer with a longitudinal quench propagation velocity of ~15 m/s. The quench propagation turn to turn is ~15 ms. The heat transfer through the insulation is in fact believed to be faster than the longitudinal propagation over an entire turn (~25 ms). The quench is detected at t=10 ms, (voltage threshold of 0.1 V). After 35 ms, the quench propagates to the second layer. The dump delay time is set to 100 ms, but the current is decreasing even before the activation time of the switch, when the power supply voltage limit (10 V ???) is reached (at ~50 ms).

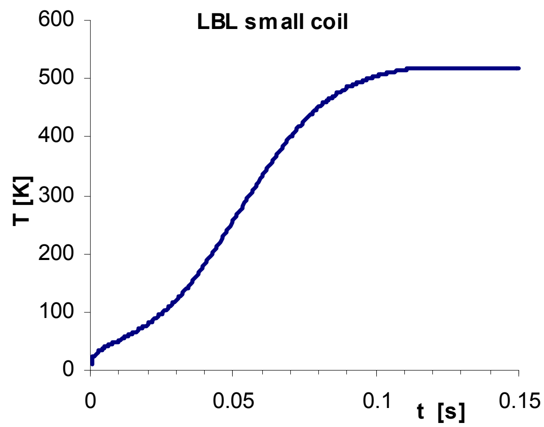

Figure 7: Temperature in the initial quench point as a function of time.

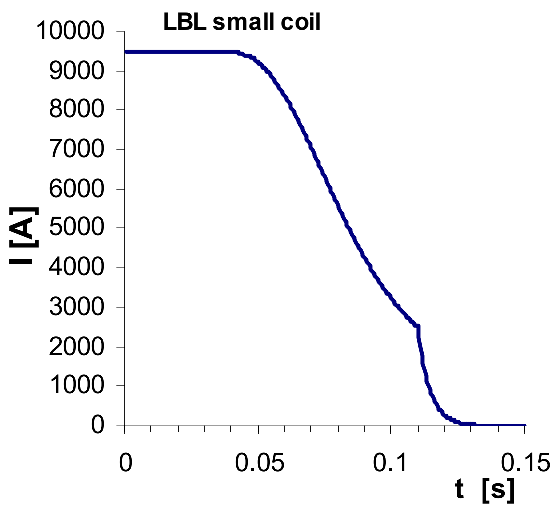

Figure 9: Current as a function of time.

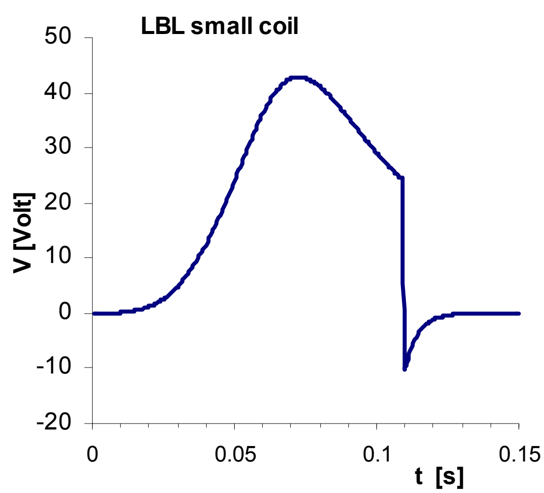

Figure 8: Voltage over first layer as a function of time.

Energy balance	**Heat deposited (kJ)**	**LHe blow off (l)**	**T peak (K)**
Layer 1	3.73	1.49	275
Layer 2	0.02	0.01	65
Whole magnet	3.75	1.50	
Dump	12.49	-	
LHe-during quench	0.03	0.01	

Table: Energy dissipated during a quench, with a dump delay time of 40 ms.

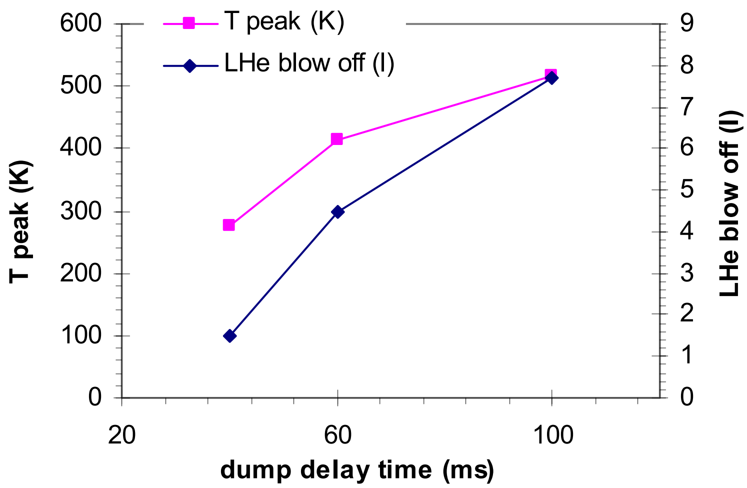

Figure 9: Summary of simulation results: peak temperature and LHe consumption for different dump delay times.

6.0 QUENCH TEST SUMMARY

The following guideline of the quench experiment is proposed:

- Quench current measurement (until close to critical current or flat plateau);
- Current ramp to a constant current below the quench current (~95%);
- Quench initiation with a spot heater;
- PS is programmed such that it dumps the current into an external resistor after quench detection signal, plus a time delay. The time delays, estimated with the present model, can be increased from 20 to 60 ms, with time steps of 10 ms;
- Analysis of the voltage data to estimate temperatures reached in the cable;
- Quench current measurement after reset of dump resistor delay to a low time value;

This sequence can be repeated until a reasonable range of peak temperatures has been explored. Resuming the simulation presented in 5.0, such a quench test would require a time-delay of 60 ms to reach temperatures of ~400 K. During this time-scale, there is not a significant heat transfer to other parts of the magnet (mechanical structure and the second module); therefore, the high temperature gradients exert a thermo-mechanical stress on the coil. The calculated boil-off rate has a peak of ~7 liters for a maximum dump delay time of 100 ms.

Therefore, we propose these measurements, because we think they are a fast track to measure the effect of high temperatures on the critical current degradation of Nb_3Sn magnets. The quench test allows an experimental support to the on going theoretical investigations at FNAL and LBNL. The first experimental results obtained at NHMFL facility on ITER cables, encourage towards a second run, performed on state of the art conductor. The high critical current in this case requires a different measurement setup. The sub-sized coil program on going at LBNL offers an opportunity to continue the experiments, with only minute changes in the instrumentation of the magnet.

APPENDIX

The spot heater for the quench test has the purpose of initiate the quench in a limited spot of the conductor. It is not suitable for measuring the minimum quench energy, because, in that case, the heater has to be smaller than the minimum quench propagation zone (typically few millimeters or less).
In figure 10 is shown the heater designed for the previous small coil tests.

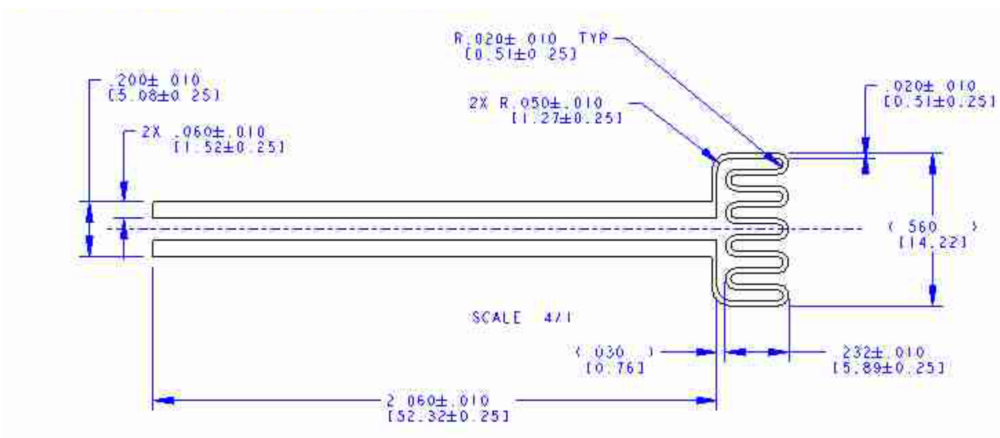

Figure 10: previous LBL spot heater design (all dimensions in inches [mm]).

In figure 11 is shown the spot heater design proposed for these quench tests. It is based on the design of the spot heaters successfully used for the HGQ models at Fermilab, but with different dimensions, such that it fits on the sub-sized cable used for the small coil winding. The advantages of the new heater design are mainly efficiency and cost.

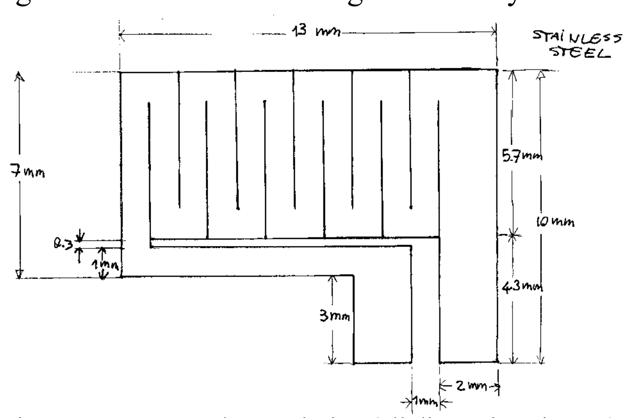

Figure 11: new spot heater design (all dimensions in mm).